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EMPLOYING SPECIES DISTRIBUTION MODELS TO BRIDGE KNOWLEDGE GAPS IN SEA TURTLE SPATIAL ECOLOGY: A GLOBAL REVIEW OF SCIENTIFIC LITERATURE

UTILIZZO DEI MODELLI DI DISTRIBUZIONE DELLE SPECIE PER COLMARE LE LACUNE CONOSCITIVE NELL'ECOLOGIA SPAZIALE DELLE TARTARUGHE MARINE: UNA REVISIONE GLOBALE DELLA LETTERATURA SCIENTIFICA

Abstract - *Sea turtles are crucial to marine ecosystems but understanding their spatial ecology is challenging due to their complex behaviour and limited availability or retrieval of occurrence data. Species Distribution Models (SDMs) are increasingly recognized for their potential to clarify distribution patterns, essential for effective conservation. However, the wide range of modelling techniques available can complicate choosing the most appropriate approach. This study reviewed the scientific application of correlative SDMs to sea turtles across 25 recent peer-reviewed articles. It found that SDMs are still underutilized, particularly in the Southern hemisphere and for most species except loggerhead and leatherback turtles. Gaps were identified in the use of environmental variables, with a lack of biotic and anthropogenic factors. Additionally, there was a tendency to favour similar modelling approaches, limiting methodological diversity. Diversifying methodologies and incorporating a broader range of environmental and biotic factors could enhance our ecological understanding in future studies.*

Keywords: *sea turtles, spatial distribution, habitat modelling, conservation, SDMs*

Introduction - Sea turtles are essential to marine ecosystems, playing a critical role due to their extensive movements and trophic chain. They travel vertically in the water column and horizontally across environments, from beaches to offshore areas. Their behaviour and ecological role make them bioindicators of marine health and sensitive to environmental changes driven by climate shifts or human activities. Protecting sea turtles is crucial for preserving marine ecosystem health and other species. However, studying their spatial ecology is challenging due to their behaviour and the difficulties of offshore research. Data, though varying by species, are often limited, discontinuous, and coastal-focused, complicating comprehensive studies. Species Distribution Models (SDMs) have gained attention for uncovering species distribution patterns, despite when fragmented data. Using statistical techniques to link species occurrence with environmental variables, SDMs help estimate and predict distributions. Their reliability, however, depends on data quality and quantity. SDMs are crucial for understanding habitat preferences, responses to temporal changes and informing management. Yet, the range of available modelling techniques can create confusion over the best approach. This study provides a global overview of peer-reviewed SDM literature on sea turtles, identifies gaps, and suggests future directions. Building on previous reviews of cetaceans and sea turtles through 2022 (Pasanisi *et al.,* 2024)—where both taxa were analysed together—this work updates the literature through mid-2024 and offers a more detailed, sea turtle-focused analysis.

Materials and methods - We performed a systematic literature search on Web of Science and SCOPUS, utilizing carefully selected search terms and operators to include word variants (Fig. 1). The final search string included the terms: "distribution model", "species distribution model", "habitat model", "niche model", "habitat suitability, "point process", "SDM", "ENM", "HSM" and "sea turtle" or "marine turtle". The search, performed in May 2024, covered all peer-reviewed papers available in scientific journals without language restrictions. Screening occurred at the title & abstract and full text. Eligible studies involved SDMs modelling sea turtle presence or distribution at sea, excluding nest locations and stranding data. We extracted data on species, study area, type of data collected, type of environmental variables included in the model, model approach and type, and outputs, organizing this information into standard categories.

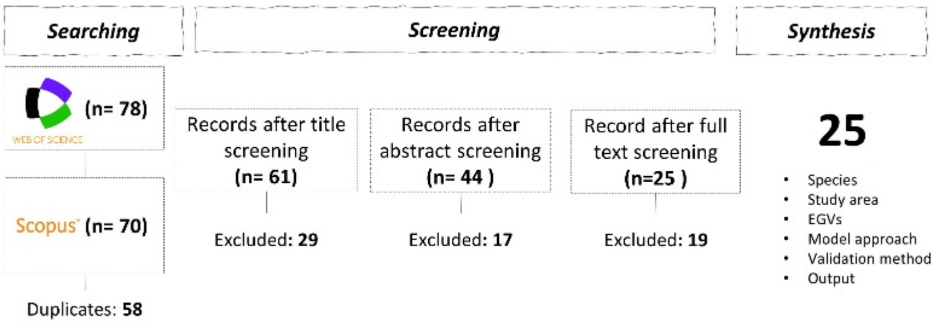

Fig. 1 - Flow diagram of the search, screening and data extraction process.
Diagramma di flusso del processo di ricerca, selezione ed estrazione dei dati.

Results - The 25 peer-reviewed papers identified reveal a limited application of SDMs to sea turtle species, with most studies being recent. While the first study (Pikesley *et al.*, 2013) appeared in 2013, interest has steadily increased, with 7 publications from 2022 to 2023 (Fig. 2A). Research efforts are primarily focused on the North Atlantic and the Pacific Ocean with less coverage in other regions of the Southern Hemisphere (Fig. 2B). Results are summarized according to the key components of SDMs: species data, environmental variables, and modeling techniques. The list of the articles is available at this link.

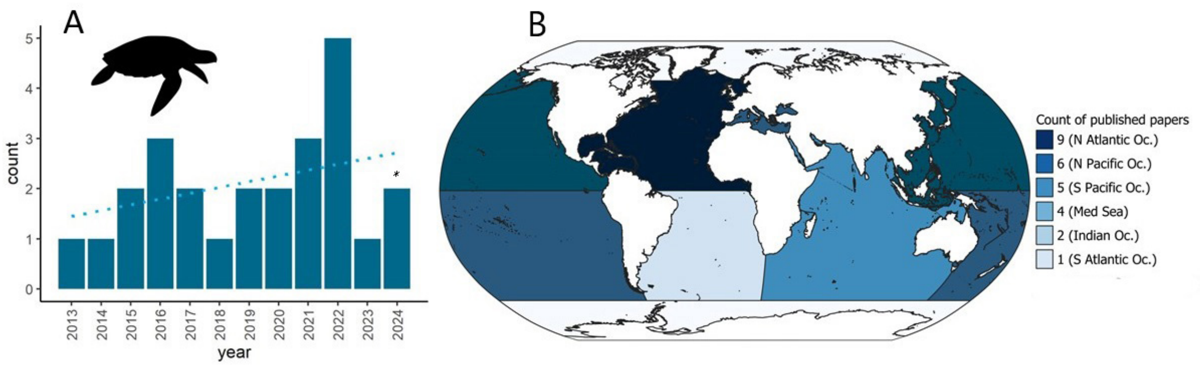

Fig. 2 – (A) Number of selected published papers over the years; (B) selected papers distribution across the globe; the asterisk next to 2024 indicates that the data for this year are incomplete (up to May).
(A)Numero di articoli selezionati pubblicati nel corso degli anni; (B) distribuzione a livello globale dei lavori scientifici selezionati; l'asterisco sul 2024 indica che i dati sono incompleti (fino a maggio).

Species data Input: The loggerhead turtle (*Caretta caretta)* and the leatherback turtle *Dermochelys coriacea* (Vandelli, 1761) dominated the study, each comprising 40% of the analysed literature. Other species were underrepresented, with only 1 to 3 studies each (Fig. 3A). Most data originated from tagging studies (60%, n=15), with visual data accounting for 40% (n=10), primarily from opportunistic surveys and open-access databases like OBIS. Short-term studies (n=15, under 10 years) were more common than long-term ones (n=7, spanning 10–30 years or more).

Environmental Variables: Sea surface temperature (SST) was the most frequently used variable (n=16), followed by bathymetry (n=12) and sea surface height (n=6). Ocean currents were studied in a few cases (n=4), while biotic and anthropogenic variables were absent (Fig. 3B). SST iconsistently emerged as the most significant factor, along with net primary production, depth and chlorophyll-a. For Atlantic leatherback turtles, SST with a 30-day lag emerged as particularly significant (Eguchi *et al.*, 2018). Similarly, sea surface height anomalies and 30-day lagged chlorophyll concentrations affect Eastern Pacific leatherbacks vertical behaviour (Barbour *et al.*, 2023).

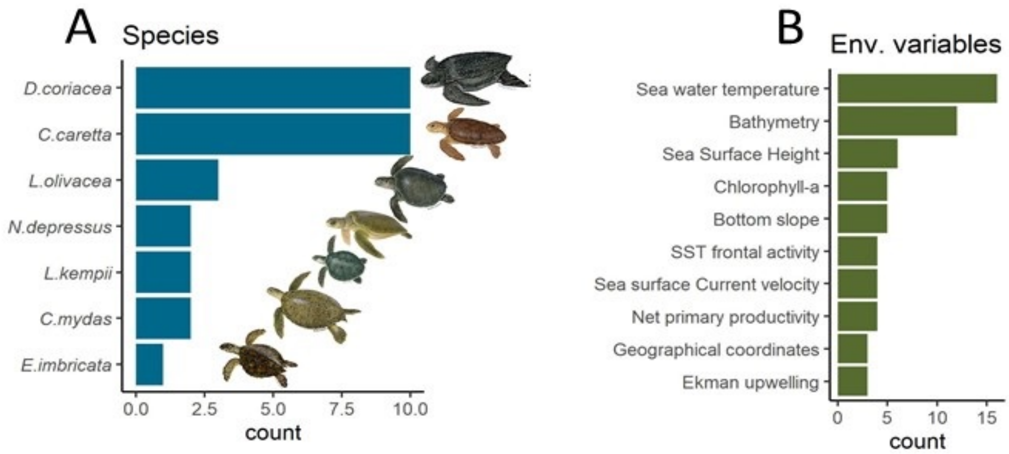

Fig. 3 – (A) Number of studies focused on each species and (B) the top ten most utilised environmental variables, including geographical variables often employed as proxies for environmental gradients or to capture spatial variability not explicitly addressed by other variables. *Dermochelys coriacea* Vandelli, 1761; *Caretta caretta* (Linnaeus, 1758); *Lepidochelys olivacea* Eschscholtz, 1829; *Natator depressus* (Garman, 1880); Lepidochelys *kempii* Garman, 1880; *Chelonia mydas* (Linnaeus, 1758); *Eretmochelys imbricata* Linnaeus, 1766.
(A)Numero di studi focalizzati su ciascuna specie (A) e le dieci variabili ambientali più utilizzate (B), incluse le variabili geografiche, impiegate come proxy per gradienti ambientali o per catturare la variabilità spaziale non esplicitata da altre variabili.

Modelling: Generating or selecting ‘pseudo-absences’ is often necessary before modelling, as most species data consist only of 'presence' points (e.g., tagging data). Reviewed studies used strategies such as: i) creating buffers around presence points and selecting random points at a distance, ii) using other species presence as a proxy for target species absence (target-method), or iii) randomly selecting points in the study area (background points). Only one study used count data for abundance predictions, and another used presence/true absence data. Common modelling approaches included machine learning (Maxent, n=10), regression models like GAM (n=10) and GLM (n=9), and esemble modelling (n=9). Emerging methods such as Point Process Models and Bayesian statistics remain underrepresented in sea turtle research.

Conclusions - Our research identifies several key areas for improving SDMs for sea turtles, which, despite their increasing application in scientific research, still exhibit significant gaps, particularly in diversifying approaches and incorporating more types of environmental variables. The scientific field has largely relied on a few modelling techniques, especially Maxent, while underexplored methods like Bayesian approaches, successful with cetaceans (Martino *et al.*, 2021), could benefit sea turtle research as

well in the future. Also, numerous other modelling frameworks offer the potential for further exploration (Valavi *et al*., 2022). A major issue is the exclusion of biotic variables (e.g., prey), despite evidence of their importance in cetacean modeling (Barlow *et al.*, 2020). Mancino *et al.* (in preparation) are leading the first effort to integrate prey modelling into species distribution models (SDMs) for Mediterranean loggerhead turtles. Similarly, anthropogenic factors, aside from one study on boat traffic (Wright *et al.*, 2022), are overlooked. Long-term datasets, crucial for capturing temporal variability in changing environments and ensuring reliable future projections, are also scarce. As SDMs become more prevalent, it is vital to employ them with a strategy that considers data quality, temporal variability, long-term datasets, seasonal changes, and the influence of biotic factors. This approach will yield more reliable results and enhance conservation strategies for these iconic and elusive species.
We recognise that focusing exclusively on SDMs and peer-reviewed articles may have limited our analysis, potentially excluding a substantial body of work utilising other modelling frameworks, such as those conducted by international organisations (e.g., RFMOs, IUCN). These sources and modelling frameworks, leveraging the extensive availability of fishery data, offer a significant contribution to deepening our understanding of species distribution patterns. Recognising this potential, future studies should aim to integrate these valuable sources while critically assessing and refining their modelling methodologies to ensure a more comprehensive overview.

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